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STRUCTURAL SIZING OF A 25 000-LB PAYLOAD, AIR-BREATHING LAUNCH VEHICLE FOR SINGLE-STAGE-TO-ORBIT

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SUMMARY

In support of NASA's Air-Breathing Launch Vehicle (ABLV) study, a 25 000-lb payload version of the GTX (formerly Trailblazer) reference vehicle concept was developed. The GTX is a vertical lift-off, reusable, single-stage-to-orbit launch vehicle concept that uses hypersonic air-breathing propulsion in a rocket-based combined-cycle (RBCC) propulsion system to reduce the required propellant fraction. To achieve this goal the vehicle and propulsion system must be well integrated both aerodynamically and structurally to reduce weight. This study demonstrates the volumetric and structural efficiency of a vertical takeoff, horizontal landing, hypersonic vehicle with a circular cross section. A departure from the lifting body concepts, this design philosophy is even extended to the engines, which have semicircular nacelles symmetrically mounted on the vehicle. Material candidates with a potential for lightweight and simplicity have been selected from a set of near term technologies (5 to 10 years). To achieve the mission trajectory, preliminary weight estimates show the vehicle's gross lift-off weight is 1.26×10^6 lb. The structural configuration of the GTX vehicle and its propulsion system are described. The vehicle design benefits are presented, and key technical issues are highlighted.

INTRODUCTION

NASA's Reusable Launch Vehicle (RLV) initiative is to reduce today's launch costs from $10,000 per pound to only hundreds of dollars per pound within 25 years. A key to enabling this low-cost goal is to design low-maintenance, reusable propulsion and vehicle systems. A single-stage-to-orbit (SSTO) vehicle would reduce recurring operation costs and enable airlinelike operations for access to space. Propulsion systems that utilize atmospheric oxygen for combustion in lieu of liquid oxygen (LO_x) dramatically reduce the weight and size of a launch vehicle. RBCC propulsion is considered promising propulsion technology for an accelerator launch vehicle. This type of vehicle uses the high-performance dual-mode ramjet for a significant portion of the ascent trajectory further reducing the vehicle size and weight.

NASA Glenn Research Center has drawn upon the technologies developed in National Aero-Space Plane (NASP), Access to Space, X–33, and RLV to assemble an integrated vehicle and propulsion system capable of SSTO operation. Key to the success of the concept is the tight integration of the vehicle with the propulsion, while maintaining an eye towards structural efficiency. This concept, known as the GTX, is a vertical takeoff, horizontal landing (VTHL) reusable SSTO launch vehicle powered by RBCC propulsion.

The purpose of this paper is to introduce the GTX ABLV conceptual design and the rationale behind the vehicle structural architecture. The vehicle gross lift-off weight (GLOW) and dry weight are determined from surface area weight factors (PSF) that will be described. This paper also shows the sensitivity to parameters such as the propellant fraction required (PFR), the equivalent effective specific impulse (I^*), and the oxygen-to-fuel (O/F) ratio. Preliminary system weight estimates will be presented and continuing work highlighted.

ABLV STUDY REQUIREMENTS

As stated earlier, two primary goals for the ABLV study require that the vehicle be SSTO and reusable. In the ABLV study, the SSTO must achieve a 220 n mi altitude at an inclination of 51.6° (Space Station Alpha) from an easterly, vertical launch. This launch at Kennedy Space Center has a window of 5 min. Performance requirements include a maximum dynamic pressure of 2000 psf, and an on-orbit/de-orbit burn allowance of 1100 ft/sec. During the trajectory, 4 g's is the maximum total acceleration with an axial acceleration limit of 3 g's. Structural factors of safety are 1.1 on yield and 1.5 on ultimate.

Hydrogen is the baseline fuel because its high energy content and heat capacity make it ideal for the RBCC SSTO mission. Liquid oxygen is the oxidizer for the rocket. Uncertainties in performance or velocity gain, ΔV, require an added reserve of 1 percent of both the ascent fuel and oxidizer volumes. Both propellants require an additional 2 percent to account for boiloff. The mission also imposes a requirement for fuel residuals of 0.5 percent, whereas the oxidizer residual requirement is only 0.3 percent. Other fuel and oxidizer requirements are 0.5 and 0.2 percent of the ascent volumes, respectively.

The design mission for the ABLV is to place a 25 000-lb payload in the International Space Station (ISS) orbit. The payload bay is required to be 15 ft wide by 15 ft high by 30 ft long. Study guidelines establish the weight and volume allowances for standard subsystems and other equipment by percentage of GLOW.

VEHICLE CONCEPTUAL DESIGN

Integration of the propulsion with the vehicle is critical in the formulation of hypersonic vehicle architecture. Both aerodynamic characteristics and structural characteristics need to be near optimum to yield an SSTO capable design. The basic vehicle configuration is pictured in figure 1. Three semicircular engine nacelles are symmetrically mounted at 120° intervals around the periphery of the vehicle's circular cross section. The engines are mounted on boundary layer flow diverters. The wings and tail are mounted on the engine nacelles to eliminate shock interaction with the engine inlet and exhaust streams. The engine nacelles provide a structural load path for the attachment of the wings and tail to stiff fuselage rings acting as a carry-through structure. The port and starboard engine nacelles must also house landing gear. The aft portion of the vehicle is sculpted to be part of the high area ratio nozzle and minimize base drag. The leading edges of the engines, wings, tail, and nose are designed as sharp as the current state-of-the-art material systems will allow, in order to minimize drag losses. The vehicle fuselage is designed to isolate the thermal distortion from aeroheating to the cryogenic propellant tanks. The propellants selected are densified liquid hydrogen (LH_2) supercooled to the triple point temperature, and LO_x cooled to the temperature of liquid nitrogen as described in reference 1.

Figure 1.—GTX Air-Breathing Launch Vehicle (ABLV) Concept.

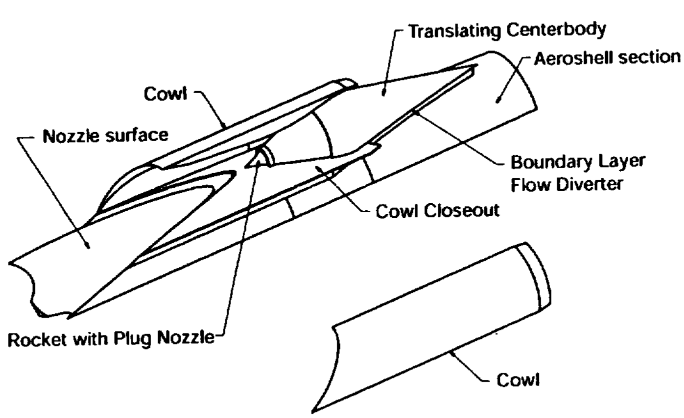

Figure 2.— GTX propulsion system cut-away view.

The circular cross-section shape was chosen for high structural and volumetric efficiency. The fuselage forebody is parabolic with a 10° half-angle nose to minimize the aero drag, while providing the requisite precompression for operation at high Mach numbers.

The GTX vehicle uses an RBCC engine, which is designed to operate from lift-off to orbit by integrating a rocket and ramjet. Shown in figure 2, the RBCC engine structure consists of a cowl, translating centerbody, and a flow diverter. A rocket element provides thrust for lift-off, low speed, and vacuum operation. During low speed from lift-off to Mach 2.5, the engine operates in an Independent Ramjet Stream (IRS) (ref. 2) cycle, from Mach 2.5 to 5.5, it operates as a ramjet, and from Mach 5.5 to 10, it operates as a scramjet. At Mach 10, the air-breathing flow path is closed by the centerbody, and the engine converts to a rocket-powered system to carry the vehicle out of the atmosphere and into orbit. More details and pictures of the propulsion system operating modes may be found in reference 3.

ENVIRONMENTAL DEFINITION

The operating loads and environment of the GTX vehicle drive the baseline architecture and material selections. Trajectory optimization studies define the environmental conditions, critical loads, and trim requirements. The following paragraphs are written to give the reader an appreciation for the complexity and magnitude of the loads.

The GTX ABLV trajectory is determined using the Optimal Trajectories by Implicit Simulation (OTIS) (ref. 4) program. Inputs to OTIS include propulsion performance, vehicle aerodynamics, flight path constraints, and the required orbit. OTIS determines the trajectory that maximizes the final mass as depicted in figure 3. Trajectory optimization is a part of an iterative process that accounts for the effects of the various constraints on structural weight.

The optimum trajectory for the GTX ABLV study appears in figure 4. The final mass in orbit is 22.4 percent of the GLOW, which translates to an I* value of 517 sec and a propellant fraction required of 77.6 percent. The overall vehicle O/F ratio for this trajectory is 2.47.

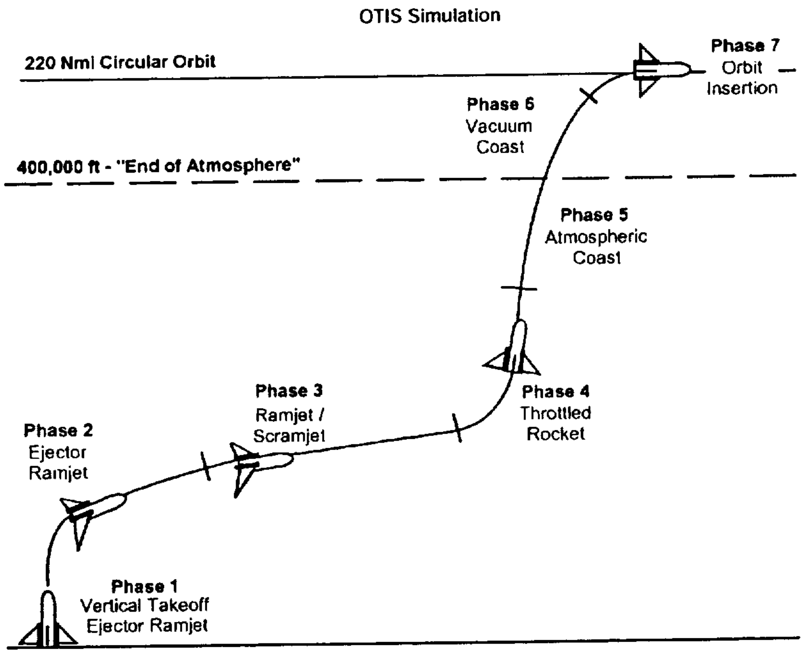

Figure 3.—GTX ABLV trajectory schematic.

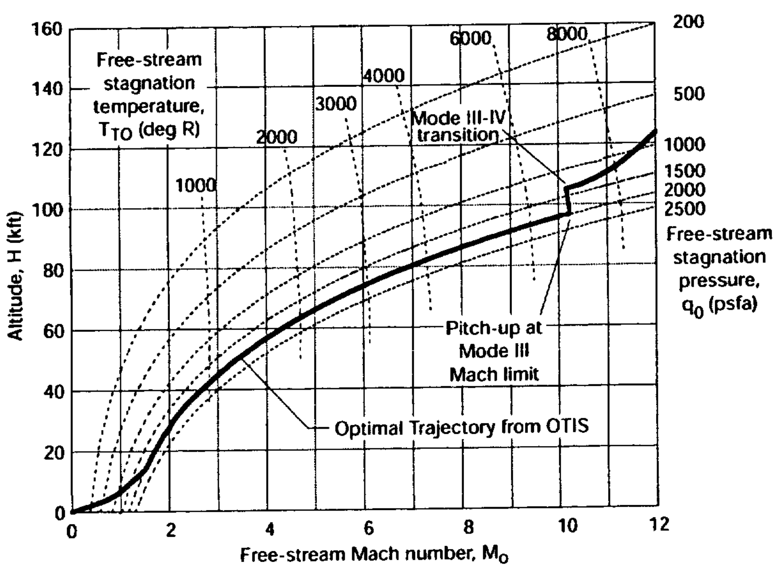

Figure 4.—GTX ABLV trajectory.

In order to generate a first order weight estimate of the engine, environmental conditions from key flight points are used.

- Takeoff (max. rocket thrust, min. aero heat transfer)
- Mach 2.5 (min. ram heat transfer, max. wing loads)
- Mach 5 (max. duct pressure)
- Mach 10 (max. heat load)

Engine duct pressures and temperatures at Mach 5 flight condition are used to select candidate materials for the engine structure. Inlet pressure reaches a maximum ΔP of 120 psia. From the combustor to the exhaust, the pressure decreases nearly linearly to the free-stream pressure.

The aerodynamic characteristics of the vehicle as functions of Mach number and angle-of-attack are evaluated using the Aerodynamic Preliminary Analysis System (APAS) (ref. 5) program. APAS is used to evaluate the lift, drag, and moment coefficients on the vehicle surfaces, as functions of flight Mach number, angle-of-attack, and elevon deflection angle.

The APAS program is also used to map skin temperatures and aeropressures on the outer skin surface of the GTX vehicle. The thermal environment is calculated using APAS and verified with the Miniature Version (MINIVER) (ref. 6) of the JA70 General Aerodynamic Heating Computer Code. The worst-case thermal environment occurs when the vehicle is pulling up to the scramjet-rocket transition point. The maximum radiation equilibrium temperature of 5200 °R occurs on the tip of the nose cone. A contour plot of the radiation equilibrium temperatures is shown in figure 5. The critical case for the vehicle occurs at Mach 10.

APAS-generated pressures are mapped onto a NASTRAN model of the GTX vehicle, which is shown in figure 6. The wing loads are worse at Mach 2.5 when the vehicle pitches over for scramjet mode and its weight is still significant.

Events from the OTIS trajectory are converted into quasi-static gravity loads for a NASTRAN analysis. The quasi-static loads were increased to account wind gusts. Since GTX is a VTHL vehicle, all lift-off inertia loads exerted on the propellant tank stack are in the vertical direction. The vehicle thrust-to-weight ratio is 1.57. This acceleration load is applied to each propellant tank along with the ullage pressure and the cryogenic temperatures of each fluid. In order to minimize tank wall thickness, the nominal tank pressures are 5 ± 2.5 psi (or 7.5 psi max.) in the GTX vehicle. During acceleration, the fluid pressure and inertial effects are modeled.

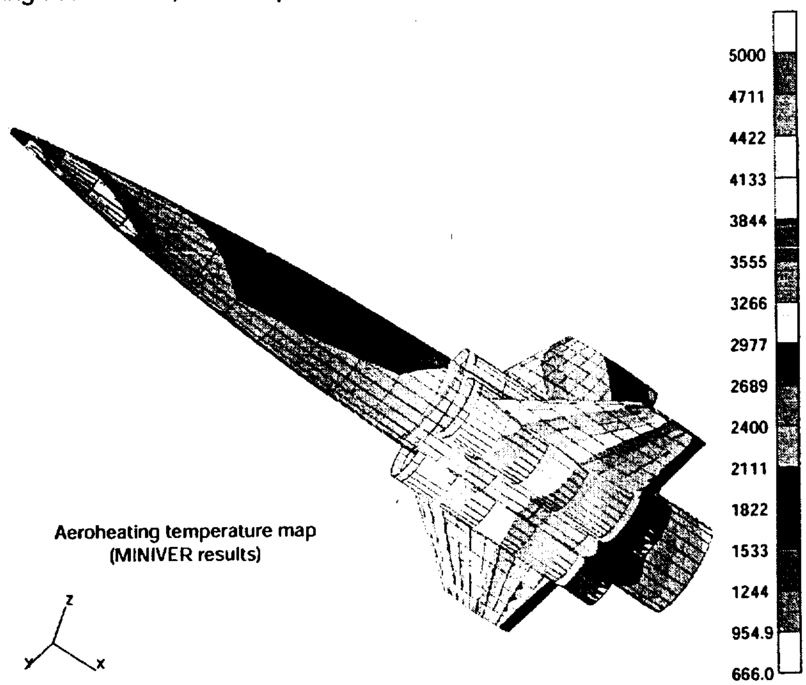

Figure 5.—GTX aeroheating temperature map at Mach 10 (°F).

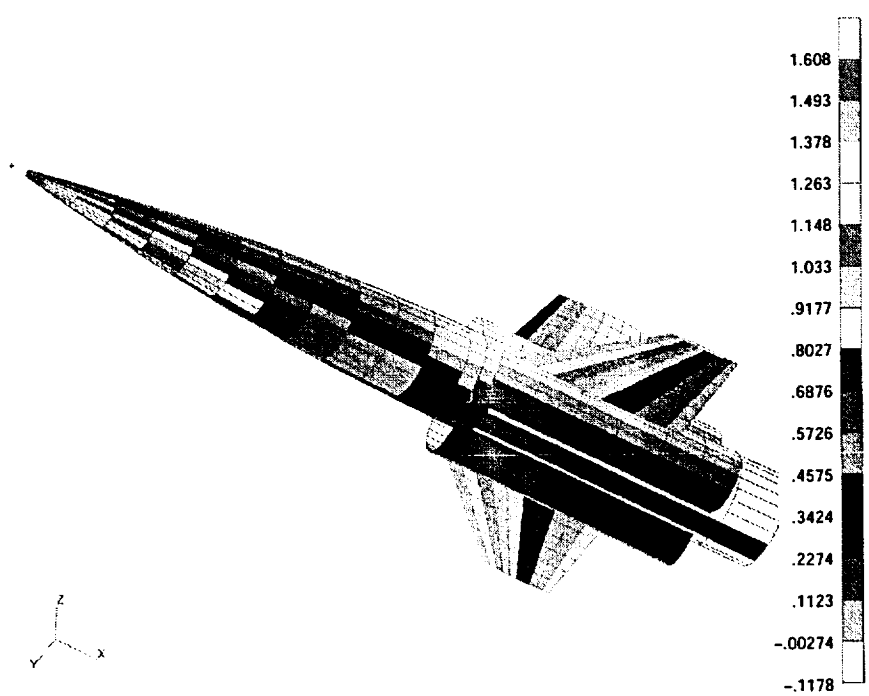

Figure 6.—GTX Mach 10 aerodynamic pressures (psi).

STRUCTURAL ARCHITECTURE AND MATERIALS

The GTX vehicle is divided into six major sections as shown in figure 7: the forebody, midbody, aftbody, propulsion assemblies, wings, and vertical tail. Together the three fuselage sections house two major internal structures: the internal cryogenic tank stack and the payload bay. Figure 8 shows the overall dimensions of baseline configuration for the GTX ABLV, known as 7c+. The GTX vehicle uses a conventional rocket tank design as pictured in figure 9. The aeroshell protects the cryogenic tanks from the aerodynamic environment.

The sharp nose tip is a passively cooled, high-conductivity carbon-carbon (CC) coated with a layer capable of handling the extreme heating expected at this location. Iridium rhenium is the candidate coating material.

The forebody is a structure composed primarily of orthogrid panels. The forebody shrouds the nose gear, electrical equipment, payload bay structure, LO_x tank, and a portion of the LH_2 tank. The forebody is reinforced with ring frames, which serve to increase buckling resistance, and to distribute aerodynamic loads from the aeroshell into the tank stack. The tank stack comprises the two cryogenic tank structures, a tank adapter between the LO_x and LH_2 tanks, and a payload adapter. This tank stack is the primary load-carrying structure supporting both the propellant and payload inertia, and reacting body-bending loads with the aeroshell.

The fuselage skins are passively cooled CC orthogrid panels. A coated CC material is selected for its high-temperature capabilities. The ring and stringer stiffeners are also made of CC material for the obvious weight and temperature advantages. A thermal protection system (TPS) comprises insulation packed within the cavities of the orthogrid lattice structure and TPS panels mounted over the internal panel surfaces and ring frames.

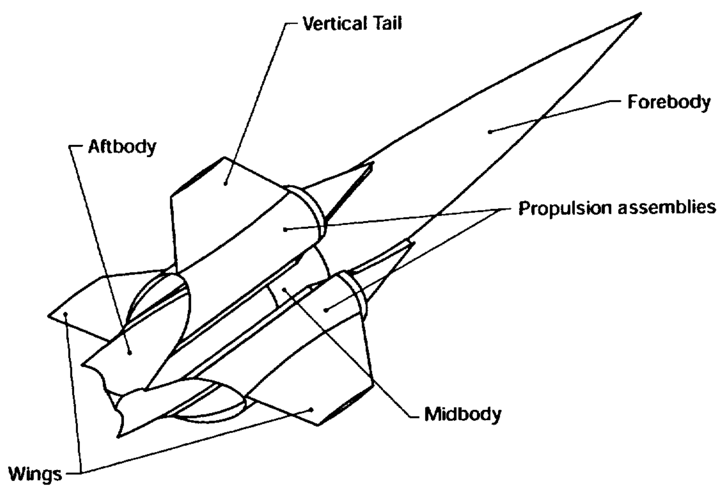

Figure 7.—GTX vehicle.

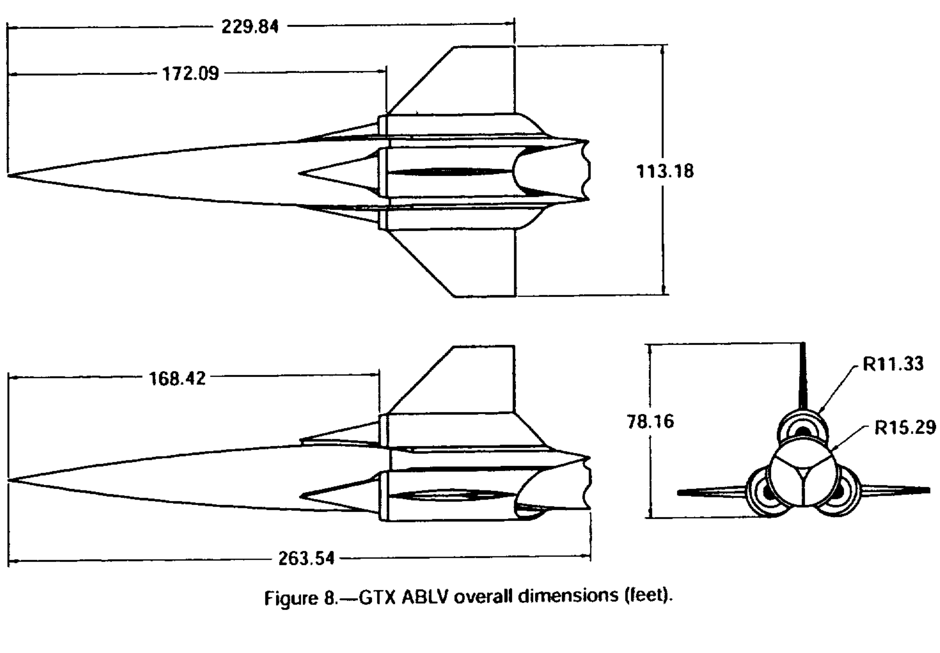

Figure 8.—GTX ABLV overall dimensions (feet).

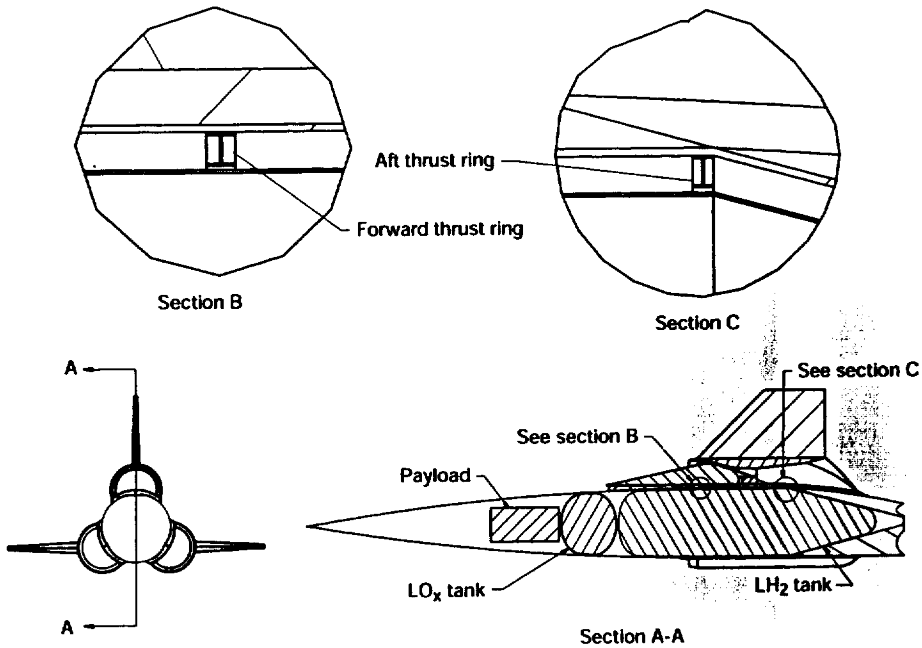

Figure 9.—GTX ABLV internal layout.

The midbody and aftbody sections enclose the LH_2 tank and provide support for the propulsion assemblies and wings. An exception to the use of composite rings occurs within these two fuselage sections near the engines where a titanium alloy is selected for its superior strength properties. Titanium rings are required in this region as load-bearing members for the engine thrust loads, wing loads, and dynamic loads from the propellant tank stack.

The engine cowls, wings, and tail are designed with an inner titanium skeletal structure of spars and ribs, which is shown in figure 10. The propulsion system must also house the main landing gear. The main landing gear is shown in an up-position in figure 11.

The propulsion system uses a combination lightweight, actively and passively cooled TPS strategy. The cowl outer skin is a CC composite coated to withstand the external aerodynamic heating environment. The cowl inner liner is a carbon-silicon carbide (C/SiC) woven integral heat exchanger with small flow passageways for regenerative hydrogen cooling. The TPS scheme used on the fuselage is applied to all surfaces facing cowl structure. Sharp leading edges of the cowl and the flow diverter are similar to the nose tip.

Hypersonic flight requires sharp leading edges on the wings for reducing drag losses. The leading edge mounting concept is shown in figure 12. The wing skins are a series of CC orthogrid panels, which are mounted on the inner titanium skeletal structure of spars and ribs. The CC wing panels are tapered from the root to the tip, in order to reduce weight. Although titanium's thermal expansion coefficient is an order of magnitude greater than CC, the thermal strains of both materials are matched by construction techniques that decouple the direct mechanical interface. Additional insulation is also used between the metallic and composite interface and above fasteners to further reduce thermal stresses.

The cross-section view of the vehicle in figure 9 shows the propellant tank stack design. The size and location of the propellant tanks are for the volumes of densified (ref. 7) LO_x and LH_2 required. These reusable cryogenic tanks and the interconnecting adapter structures are to be constructed from PMC. This material is chosen for its strength to weight ratio, ease of construction, and fluid compatibility. The stiffeners are tapered from the propulsion zone of the fuselage to the nose tip for weight optimization.

The hydrogen tank is mounted about its circumference to the forward and aft thrust rings (fig. 9) at two locations by a series of struts. The forward LH_2 tank attachment supports the tank stack to the fuselage in all directions. The aft tank attachment scheme is designed to isolate the differential thermal expansion and displacements due to flight dynamics between the tank and the fuselage. The aft attachment allows the tank to distort without inducing thermal or mechanical stresses.

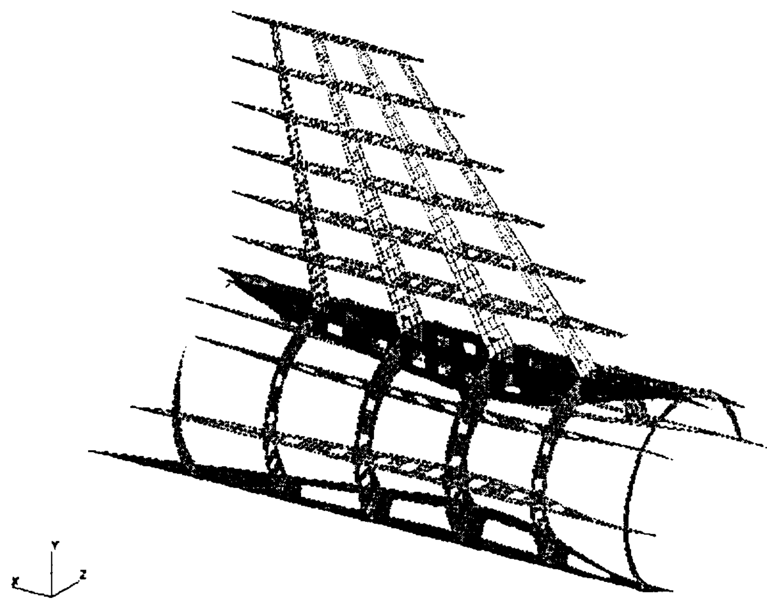

Figure 10.—Wing-cowl substructure.

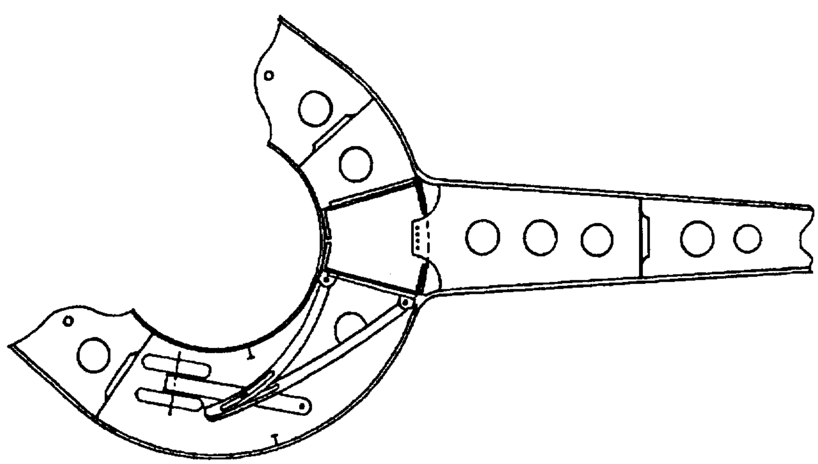

Figure 11.—Cowl-wing—landing gear concept.

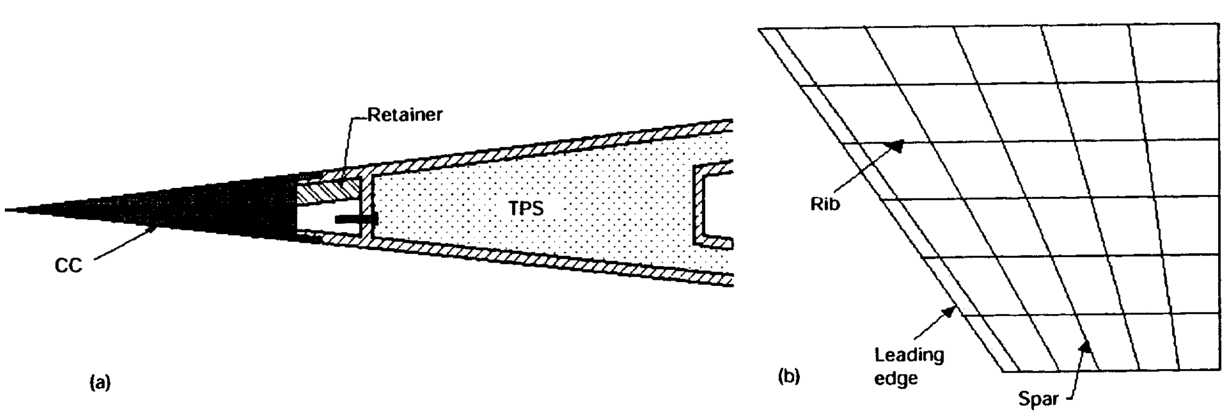

Figure 12.—Wing leading edge.

PRELIMINARY STRUCTURAL SIZING

Two methods are available for estimating the weight of flight vehicles and their substructures. The first method is the empirical "top-down" approach, which requires the knowledge of similar existing structures and vehicle scaling relationships. The other method is a detailed "bottoms-up" approach, which requires detailed structural analysis of the vehicle. Each method has particular advantages and limitations in the weight estimation of an SSTO. A hybrid approach can be used to increase the accuracy of sizing the large structures while subsystems may be estimated with a top-down approach.

Developing a hybrid approach involves creating a detailed geometry of the primary structure and applying areal weight factors. Areal weights are developed from stress analysis and historical data. Weights and volumes of secondary structures and subsystems from the study requirements and historical data are scaled to match the vehicle size.

The GTX ABLV vehicle has two significant design features that affect stability and control: (1) the propellant tank shapes and sizes and (2) the placement of the payload and propellant tanks. These two design considerations are interrelated, and they affect vehicle closure.

OTIS is used to study the effect of changes in the vehicle's center of gravity (c.g.) as propellants are depleted. Using CAD, both the LH_2 and LO_x are modeled in the shape of their respective tanks. Then, assuming acceleration always pushes the liquid aft, the forward ends are incrementally cut, and a new vehicle c.g. is calculated. Using Excel®, the vehicle c.g. versus propellant remaining results are tabulated and graphed in a "carpet" plot for the trajectory team. As shown in figure 13, propellant usage in GTX has significant effects on the vehicle c.g. Based on preliminary trajectory results, stability and control is improved by moving the vehicle c.g. 40 feet aft.

Referring to table I, LO_x is the heaviest item on the vehicle, and its location controls the vehicle c.g. When one moves the LO_x tank aft, the overall vehicle c.g. would move aft. However, the square cross-sectional shape of the payload bay (dictated by the ABLV study) limits layout changes within a round body. The payload bay can only move so far forward before it interferes with the parabolic nose shell walls. The solution to this packaging problem is a conformal LH_2 tank design, as shown in figure 9. This design change provides space between the LH_2 tank and the payload bay for a more compact LO_x tank. The vehicle c.g. moves aft with the LO_x tank, and the compact design minimizes the shift in the vehicle c.g. as propellants are depleted improving both stability and control.

VEHICLE CLOSURE

When the PFA in the vehicle is equal to or greater than the PFR to fly the trajectory, then the vehicle is considered "closed." Determining vehicle closure is an iterative process. This process involves the calculation of propellant tank sizes, the propellant weight, and the vehicle weight. This is used to determine the PFA, which is compared to the PFR. Adjustments are made as required.

Preliminary weight estimate for the GTX ABLV used a semi-empirical approach. An Excel® workbook was created in which individual spreadsheets for each major component (i.e., fuselage, wings, and tanks) calculated the surface area, volume, and weight. Other items (i.e., landing gear, hydraulics, and avionics) used reference data from the ABLV ground rules document, Roskam (ref. 8), and other sources in an empirical approach.

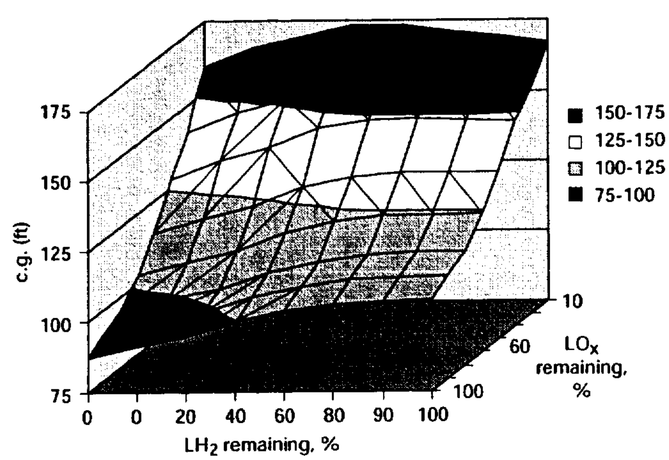

Figure 13.—GTX vehicle c.g. as a function of propellant remaining.

Once the vehicle body radius and the engine inlet area are determined, the propellant tanks are defined by the vehicle geometry. The propellant weights for the ascent trajectory are estimated from the PFR and vehicle O/F ratio. Additional amounts of propellant are added to account for ascent margins, residuals, boil-off, on-orbit/de-orbit burn, and other uncertainties.

Subsequent to closure, new lift and drag coefficients that include elevon moments are calculated for OTIS trajectory analysis. OTIS calculates new values of the PFR and the O/F ratio. The GTX vehicle size and weight statement are verified. The final GLOW and c.g. location for the GTX ABLV are given in table I. The vehicle GLOW is 1.25×10^6 lb with a dry weight of 178 900 lbs. With a 25 000-lb payload, the empty weight fraction is approximately 14 percent for the GTX ABLV.

TABLE I.—WEIGHT SUMMARY FOR THE GTX ABLV

Assembly	Components	Volume, (cu-ft)	Weight, (lbs)	Subtotal weight, (lbs)	C.G. from tip x (ft)	y (ft)	z (ft)
Aero-shells				20,700.39			
	Parabolic fairing	140	13,126.95		108	0	0
	Midbody shell	10	3,035.21		187	0	0
	Aft adapter/nozzle	36	4,538.23		237	0	0
Structures				6,379.48			
	Add'l fuselage struct	15	2,384.46		100	0	0
	Payload adapter	25	3,995.02		100	0	3
TPS				11,193.07			
	H_2 tank cryo	1,192	1,478.20		188	0	0
	O_x tank cryo	339	203.64		125	0	0
	Fuselage TPS	2,536	9,511.24		148	0	0
Propellants				1,044,337.41			
	H_2 liquid	67,842	293,984.08		188	0	0
	O_x liquid	10,734	750,353.34		125	0	0
Tanks				13,447.32			
	Liquid H_2 tank	838	7,205.01		188	0	0
	Liquid O_x tank	256	3,697.77		125	0	0
	Helium bottles (full)	14	2,544.54		206	0	0
3 Engines (7c+ config)				69,456.78			
	Center bodies	186	9,164.97		176	0	0
	Cowls	1,026	41,243.34		202	0	0
	Rocket nozzles	246	7,500.00		197	0	0
	Closeouts	387	3,114.69		191	0	0
	Flow diverters	7,599	8,433.75		192	0	0
Wings				22,230.60			
	Tail	1,138	7,086.36		211	0	42
	Left wing	1,834	7,572.12		211	−40	−9
	Right wing	1,834	7,572.12		211	40	−9
Payload				25,000.00			
	Cargo	6,750	25,000.00		97	0	0
Landing gear				9,512.73			
	Nose gear	523	2,145.64		97	0	−8
	Main gear	1,047	7,367.09		202	0	−11
Equipment				25,955.23			
	AVTCS	398	3,728.35		194	0	0
	ECLSS	322	1,290.41		93	12	0
	EPD&C	206	1,232.15		97	−12	0
	Hydraulics	647	6,924.03		150	0	0
	APU	542	1,717.68		97	12	0
	RCS	368	1,250.21		132	0	0
	VPP&D	319	1,700.68		100	0	0
	Oxygen delivery	470	4,512.54		157	0	0
	Fuel delivery	200	1,926.82		230	0	0
	Avionics (VMS)	193	1,672.35	**Wt Goals**	97	0	12
TOTALS	Dry vehicle (w/o payload)		178,875.59	**198,574**	177	0	1
	Dry vehicle		203,875.59	**223,574**	167	0	0
	Wet vehicle	110,210	1,248,213.00	**1,252,617**	147	0	0

CONCLUDING REMARKS

RBCC-powered VTHL launch vehicles appear to enable reusable SSTO launch operations. The propulsive performance increase appears adequate to offset the additional system weight. More in-depth analyses are warranted.

The development of the ABLV configuration required evolving a 300-lb-payload vehicle concept to a 25 000-lb-payload vehicle. The scaling laws used were reasonable, however, detailed structural analysis is required to anchor the ABLV concept. To date reentry loads and acoustic loads have had cursory evaluations and require more detailed assessments for the impact on vehicle weight. In addition the preliminary sizing model needs additional flexibility in the area of the TPS sizing. Both Q and terminal air-breathing Mach number should be optimized in the preliminary sizing algorithms. Complete utilization of the fuselage volume is essential to weight minimization, and c.g. location requirements for vehicle trim drive the need for additional tank configuration trade studies

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